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CORE POWER AND DECAY TIME LIMITS FOR A
DISABLED LOFT ECCS

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SUMMARY

An analysis was done to determine at what LOFT total core power (nuclear plus decay power) the ECCS could be inoperable. The criteria used for the analysis was that the maximum fuel clad temperature should not exceed 1650⁶F given a loss of coolant. Calculations for natural convection cooling of the fuel by air with an inlet temperature of 580⁰F determined that the limiting core power is 25kW (discounted by 15% to 20% for potential uncertainties). This limiting decay power corresponds to the following shutdown times after LOFT operation:

Operating Power MW	Operating Time	Shutdown Time
50	2 days (48EFPH)	2.6 days
50	8.3 days (200 EFPH)	8.5 days
50	83 days (2000 EFPH)	50 days
1	∞	7 minutes

Therefore, the LOFT ECCS can be safely bypassed or disabled after the above shutdown times or during operation at very low power (a total core power not exceeding 25 kW).

CORE POWER AND DECAY TIME LIMITS FOR A
DISABLED LOFT ECCS

I. DESCRIPTION OF THE PROBLEM

The Emergency Core Cooling System (ECCS) for the LOFT reactor may need to be disabled for modifications or repairs of hardware or instrumentation or for component testing during periods when the reactor system is hot and pressurized, or it may be desirable to enable the ECCS to be disabled without the necessity of cooling down and depressurizing the reactor. Therefore, an analysis, discussed in this report, was done to determine the total core power (nuclear power plus decay power) and/or the shutdown (decay) times for which the ECCS could be safely disabled given a loss of coolant.

The assumed conditions for the reactor prior to the assumed loss of coolant are:

- (a) The reactor has been shutdown after operation at powers up to 50 MW. The shutdown mode is either mode 3 (intermediate shutdown with a coolant temperature between 200°F and 500°F) or mode 4 (hot shutdown with a coolant temperature close to 500°F).
- (b) The reactor has been shutdown after having operated at a low power (not exceeding 1 MW), and the coolant temperature is close to 500°F.
- (c) The reactor has been operated at a very low power level for zero-power physics tests. The coolant temperature is less than 500°F. (Enveloped by (b), above).

II. SAFETY CRITERIA

The criteria used for determining when the ECCS would not be needed following a loss of coolant was a maximum (peak) fuel clad temperature of less than 1650°F. This maximum clad temperature (TMAX) is obtained from the damage criteria established for the LOFT Technical Specifications⁽¹⁾ for Infrequent Incidents (Unlikely Faults). Loss of coolant accidents are considered to have a qualitative probability for occurrence less than that for a Limiting Fault (or Extremely Unlikely Fault) for both the LOFT reactor and for the nuclear industry. The damage criteria specified in the LOFT Technical Specifications for Limiting Faults would allow TMAX to be up to 2200°F as long as no more than 244 fuel pins have a clad temperature exceeding 1900°F (see Reference 1 for other limiting conditions for the Limiting Fault damage criteria). Therefore, use of $TMAX < 1650^{\circ}F$ is a conservative and sufficient criteria for use in determining when ECCS would not be required following a loss of coolant. With a maximum clad temperature of 1650°F a small amount of damage may exist to some of the LOFT fuel pins (necessitating replacement), but any significant fuel pin perforation would not be expected.

III. ANALYSIS METHODS AND ASSUMPTIONS

The analysis was based on a study in Reference 2 for natural convection cooling of LOFT fuel modules by air when stored at the TAN Hot Shop. The methods and equations used in Reference 2 for vertical fuel modules are applicable to fuel modules in the LOFT core. The equations developed in Reference 2 and used for the analysis for disabled ECCS limits are:

$$T_{MAX} = T_{IN} + (1.5084E-3)Q((352.37/\overline{MCP})(\sin(3.048X_{MAX})+0.96675) \\ + (9.0515/h)\cos(3.048X_{MAX}))$$

$$X_{MAX} = 0.3281 \tan^{-1}(35.305h/\overline{MCP})$$

$$Q = \overline{MCP}(T_2 - T_{IN}) = \overline{MCP}(DT_2)$$

$$M = 5860(\overline{\rho}(\rho_{IN}-\overline{\rho}))^{1/2}$$

$$h = 4.5\overline{MCP}(\overline{\mu}/\mu_2)^{.14}/(0.20607NRe)$$

$$= 21.837\overline{MCP}(\overline{\mu}/\mu_2)^{.14}/NRe$$

$$NRe = 4.684M/\overline{\mu}$$

$$\rho_{IN} = 33.1/T_{IN}^1$$

$$\overline{\rho} = 33.1(\ln(T_2^1/T_{IN}^1))/(T_2^1-T_{IN}^1)$$

$$= 33.1(\ln(T_2^1/T_{IN}^1))/DT_2$$

$$T_2^1 = T_2 + 460$$

$$T_{IN}^1 = T_{IN} + 460$$

T_{MAX} (°F) = maximum fuel clad temperature.

X_{MAX} (inches) = location above (downstream of) the hot spot (point of peak power) at which the clad temperature on the hot pin is T_{MAX} .

Q (Btu/hr) = the average fuel module heat generation rate.

M (lbm/hr) = the mass flow rate of air through the fuel module.

h (Btu/hr-ft²-°F) = heat transfer coefficient for natural convection to air.

NRe = Reynold's number.

ρ_{IN} = density of the air at the inlet to the module.

$\overline{\rho}$ = average density of the air in the hot channel of the modules up to X_{MAX} .

T_2 (°F) or T_2^1 (°R) = temperature of the air at X_{MAX} .

T_{IN} (°F) or T_{IN}^1 (°R) = temperature of the air at the inlet to the fuel module.

$\overline{CP}$ (Btu/lbm-°F) = specific heat of the air calculated at the average air temperature in the hot channel up to X_{MAX} ($\overline{T}$).

$\bar{\mu}$ (lbm/ft-sec) = viscosity of the air calculated at $\bar{T}$.

μ_2 (lbm/ft-sec) = viscosity of the air at T_2 .

These equations are for the center (hot) fuel module for LOFT operation at 55 MW. The center module power is 12.485 MW when the reactor operates at 55 MW⁽²⁾.

The LOFT core power is calculated by:

$$\begin{aligned} P(\text{kW}) &= (Q(\text{Btu/hr})/3.414\text{E3}(\text{Btu/MW-hr}))(55/12.485) \\ &= (1.29\text{E-3})Q \end{aligned}$$

The method of solution is to assume a value for T_{IN} and T_2 , then to calculate the corresponding heat removal rate in the fuel module, or Q and the maximum clad temperature (T_{MAX}). Then calculate the core power which corresponds to a heat removal rate of Q from the center fuel module. This solution method can be iterated upon to find the power (P) at which $T_{MAX} = 1650^\circ\text{F}$.

The values for $\overline{CP}$, $\bar{\mu}$, and μ_2 are obtained from the figures on pages 5A and 5B of Appendix A of Reference 2.

An analysis was also made to determine if the head differences for natural circulation of air through the LOFT Primary Coolant System (PCS) are sufficient to support natural convection flow through the system. The analysis for natural circulation of air through the PCS was based on the simplified momentum equations for natural circulation developed in Reference (4). For the LOFT PCS as modeled in Figure 3:

$$P_1 - P_2 = (RD)G^2 + \bar{\rho D} (H_2 - H_1)$$

$$P_2 - P_3 = (RC)G^2 + \bar{\rho C} (H_3 - H_2)$$

$$P_3 - P_1 = (RL)G^2 + \bar{\rho L} (H_1 - H_3)$$

P = Pressure

R = Flow resistance (friction Loss)

G = Volumetric flow rate

$\bar{\rho}$ = Average fluid density

H = elevation

These equations neglect the bypass flow through the vessel since it is much less than the flow through the core. Adding these equations together to obtain the momentum balance around the PCS, yields:

$$(RD+RC+RL)G^2 + \bar{\rho}_C * LC + \bar{\rho}_L * LU - \bar{\rho}_D * LD = 0$$

$$LC = H3-H2$$

$$LD = H1-H2$$

$$LU = H4-H3 = H1-H3$$

$$G = \left[\frac{\bar{\rho}_D * LD - \bar{\rho}_C * LC - \bar{\rho}_L * LU}{(144)(\Sigma R)} \right]^{1/2}$$

$$\Sigma R = RD + RC + RL$$

$$R = \frac{\Delta P \text{ (friction)}}{G^2}$$

Values for R were derived from data in Reference (5) for ΔP versus flow in the LOFT PCS, and from the values for loop resistance given in Reference (6). The resistance is actually comprised of a number of terms as in the following equation:

$$R = \left(f \frac{L}{D_e} + K \right) \frac{\rho}{2g_c A_c^2}$$

f = friction factor

L = channel length

D_e = hydraulic diameter

k = form loss factor

A_c = cross sectional flow area

Since the resistance derived from information in Reference (5) and (6) are for water as the fluid, then the resistances have to be corrected for use with air. As seen by the above equation,

$$R = R^{\partial} \rho$$

$$\text{where } R^{\partial} = \frac{(f \frac{L}{D_e} + K)}{2gc \cdot Ac^2} = \frac{R}{\rho}$$

Values for R^{∂} were calculated, and used for the analysis for natural circulation of air through the PCS loop in the following equation:

$$\Sigma R = R D^{\partial} \overline{\rho D} + R C^{\partial} \overline{\rho C} + R L^{\partial} \overline{\rho L} \quad (\text{EQ.1})$$

$$R D^{\partial} = 5.39 \times 10^{-4} \text{ Psi} / (\text{ft}^3/\text{sec})^2 / (\text{lbm}/\text{ft}^3)$$

$$R C^{\partial} = 3.7 \times 10^{-4} \text{ Psi} / (\text{ft}^3/\text{sec})^2 / (\text{lbm}/\text{ft}^3)$$

$$R L^{\partial} = 1.12 \times 10^{-3} \text{ Psi} / (\text{ft}^3/\text{sec})^2 / (\text{lbm}/\text{ft}^3)$$

The heat transfer equations through the PCS loop are:

For the downcomer

$$h D \cdot A D (\overline{TSD} - \overline{TD}) = G \cdot \overline{\rho D} \cdot \overline{CP} (T2 - T1)$$

For the core

$$h C \cdot A C (\overline{TSC} - \overline{TC}) = G \cdot \overline{\rho C} \cdot \overline{CP} (T3 - T2)$$

For the balance of the loop

$$h L \cdot A L (\overline{TSL} - \overline{TL}) = G \cdot \overline{\rho L} \cdot \overline{CP} (T0 - T3)$$

h = heat transfer coefficient, calculated by the previous equation for h .

A = heat transfer area.

$\overline{TS}$ = average surface temperature in the channel.

$\overline{T}$ = average air temperature in the channel.

$T0$ = loop outlet temperature

The analysis was simplified by using constant values for h , since the heat transfer coefficient does not vary significantly in any given channel in the model. For the downcomer (channel D), $h \sim 1.86 \text{ BTU/hr-ft}^2 \text{ } ^\circ\text{F}$. For the core (channel C), $h \sim 2.5 \text{ BTU/hr-ft}^2 \text{ } ^\circ\text{F}$. for the balance of the loop, $h \sim 2.0 \text{ BTU/hr-ft}^2 \text{ } ^\circ\text{F}$.

The surface area of the downcomer was calculated as 351.8 ft^2 . The surface area of the core is 789.93 ft^2 ^(b). The lengths of the vertical channels of interest are ⁽⁵⁾.

$$LD = 13.74 \text{ ft}$$

$$LC = 5.49 \text{ ft.}$$

$$LU = 8.25 \text{ ft.}$$

$\overline{CP}$ for air can be taken to be a constant with a value of $0.25 \text{ BTU/lbm-}^\circ\text{F}$.

Then for G in units of ft^3/sec , the equations for natural circulation of air through the PCS become:

$$T_2 = T_1 + \frac{(0.52)(\overline{TSD} - \overline{TD})}{G\overline{pD}} \quad (\text{EQ.2})$$

$$T_3 = T_2 + \frac{(2.19)(\overline{TSC} - \overline{TC})}{G\overline{pC}} \quad (\text{EQ.3})$$

$$G = \left[\frac{(13.74 \overline{pD} - (5.49) \overline{pC} - (8.25) \overline{pL})}{(144) (\Sigma R)} \right]^{1/2} \quad (\text{EQ.4})$$

$$\overline{p} = \frac{33.1 \ln \left(\frac{T_{out} + 460}{T_{in} + 460} \right)}{T_{out} - T_{in}} \quad (\text{EQ.5})$$

The surface temperature in the downcomer was taken as 580°F . The average surface temperature in the core, when the peak clad temperature is 1650°F and for an assumed core inlet temperature of 500°F , is calculated as:

$$\overline{TSC} \approx \frac{1650 - 500}{2.5} + 960^{\circ}\text{F}$$

The factor of 2.5 is the peak to core average power ratio for the LOFT Core-I⁽⁷⁾ for balanced CRA's. Higher peaking may occur during operation with unbalanced CRA's during Zero Power Physics Testing, but such operation will be at very low powers (200 kW or less) and short times such that the decay power will not be significantly affected. After some initial calculations, the solution was simplified further by assuming that the average air temperature for the balance of the loop is 1000⁰F (the air is cooled as it passes through the balance of the loop after having passed through the core). Therefore, $\overline{\rho L} \approx 0.0227 \frac{\text{lbm}}{\text{ft}^3}$. The solution procedure for the analysis for natural circulation of air through the PCS loop is diagramed in Figure 4.

IV ANALYSIS RESULTS

The analysis for natural circulation of air through the LOFT PCS loop gave the following results:

Volumetric air flow - - - - - 7.5 ft³/sec.

Downcomer exit temperature - - - - - 523⁰F

Average core exit temperature - - - - - 1271⁰F

The analysis shows that substantial natural circulation of air would flow through the LOFT PCS (given a hot core), and that the core inlet temperature will be approximately 520⁰F for a cold leg break and a downcomer surface temperature of 580⁰F. However, a hot leg break could result in a higher air inlet temperature to the core, possibly reaching the temperature of the downcomer or 580⁰F.

The result of calculations for decay heat removal using the equations in Section III for different assumed values of T_{IN} and T₂ are tabulated in the following tables, I (for T_{IN}=500⁰F), II (for T_{IN}=400⁰F), and III (for T_{IN}=300⁰F), and are plotted in Figure 1. Figure 1 (which plots T_{MAX} vs P) can be used to determine P for T_{MAX}=1650⁰F. Figure 2 plots P vs T_{IN} for T_{MAX}=1650⁰F, and for

$T_{MAX}=1900^{\circ}F$. From Figure 1, the limit on total core power (nuclear power plus decay power) for $T_{MAX} < 1650^{\circ}F$ is:

<u>$T_{IN}(^{\circ}F)$</u>	<u>$P_{MAX}(kW)$</u>
300	52.8
400	42.8
500	35.0

The limiting total core power (P_{MAX}) for a given limit on T_{MAX} is seen to be a function of the air temperature at the inlet to the fuel module (at the fuel module bottom). As the air enters the primary coolant piping (at the break, after blowdown and draining has occurred) it will be heated up by heat transfer from the pipe walls, from the walls of the downcomer, and by steam in the system. The heat removal capacity of steam or an air-steam mixture is much greater than that of air. Therefore, assuming that the heat transfer fluid is "dry" air, as was done in Reference 2 and in this analysis, is conservative.

The calculated value for P_{MAX} needs to be discounted for the potential inaccuracy in decay power calculations or in measuring reactor power at very low power levels. For shutdown (decay) times between 10^3 and 10^7 seconds, the decay power as calculated by the curves or equations of Reference 3 may have an uncertainty of 10% to -20%. The inaccuracy in knowing the reactor power level is unlikely to be significantly greater than this. Therefore, the limiting total core power (nuclear plus decay heat) for a maximum fuel clad temperature of $1650^{\circ}F$ and a core inlet temperature of $523^{\circ}F$ for natural convection cooling of the LOFT fuel by air following a loss of coolant is 28 kW. This value for P_{MAX} has been discounted by 17% from the value calculated using the previously described analysis methods. For a core inlet temperature of $580^{\circ}F$, the limiting decay power is 24 kW (discounted 20%) to 25 kW (discounted 16%).

This limiting total core power can be defined in terms of shutdown or decay time for use when the reactor has been shutdown, by using the decay power curves or equations in Reference 3. For $P_{MAX}=25\text{kW}$ and an operating power (P_0) of 50 MW ($50 \times 10^3 \text{ kW}$), $P/P_0=5.0 \times 10^{-4}$. Then, from Reference 3 or using Figure 5 from Reference 2:

<u>Operating Time</u>	<u>Required shutdown time after Operating at 55 MW</u>
2 days (48 hours)	2.6 days (62 hours)
8.3 days (220 hours)	8.5 days
83 days (2000 hours)	50 days

For low power operation at a reactor power not exceeding 1 MW , and a decay Power of 24 kW , $P/P_0=0.024$. From Reference 3:

$$P/P_0(t_0, t_s) = P/P_0(\infty, t_s) - P/P_0(\infty, t_0 + t_s)$$

where

$$P/P_0(\infty, t) = At^{-a}$$

if $t_s \ll t_0$, as it will be for the low power operation case, then

$$P/P_0(t_0, t_s) \sim At_s^{-a} - At_0^{-a}$$

Then,

$$t_s (\text{shutdown time}) = (A/(P/P_0 + At_0^{-a}))^{1/a}$$

The values for the constants A and a are: ⁽³⁾

<u>t_s (sec.)</u>	<u>A</u>	<u>a</u>
$10^{-1} \leq t_s \leq 10^1$	0.0766	0.181
$10^1 \leq t_s \leq 150$	0.0603	0.0639
$150 \leq t_s \leq 4E6$	0.130	0.283

If infinite operating time is assumed, $t_0 = \infty$ and for $t_s > 150\text{ sec.}$,

$$t_s = (A/(P/P_0))^{1/a} = (0.130/(0.024))^{1/0.283} = 415\text{ sec.} = 7\text{ minutes.}$$

As seen by the above results even if infinite operating time is assumed, a shutdown power less than 24 kW can be assured after a shutdown time of only 7 minutes after operating at 1 MW. Therefore, the ECCS could be bypassed or disabled 7 minutes after shutdown when the reactor has not operated at more than 1 MW without the maximum fuel clad temperature exceeding 1650°F should a loss of coolant occur at that time.

V. CONCLUSIONS

The conclusions of this analysis are:

- (a) The ECCS can be safely bypassed or disabled if the maximum fuel clad temperature will be less than 1650°F (the fuel clad temperature damage limit for Infrequent Incidents) given a loss of coolant from the reactor.
- (b) The maximum fuel clad temperature will be less than 1650°F for natural convection cooling of the LOFT fuel by dry air if the total core power (nuclear plus decay power) is less than 30 kW. The actual limit on core power should be 25 kW to allow for 16% to 20% uncertainty for decay power calculations (using Reference 3).
- (c) The required shutdown (decay) time after full power operation at 50 MW to reach decay power less than 25 kW is:

<u>Operating Time</u>	<u>Shutdown Time</u>
2 days (48 EFPH)	2.6 days
8.3 days (200 EFPH)	8.5 days
83 days (2000 EFPH)	50 days

- (d) The required shutdown time after operation at a power not exceeding 1 MW to reach a decay power less than 24 kW (allowing for a 20% uncertainty) for any operating time is 7 minutes.

VI. REFERENCES

1. "LOFT Technical Specifications", Revision 1, Sept. 7, 1977, Section 3.13
2. LTR 17-27, "LOFT Post-Test Fuel Handling in Air", H. F. Rhodes, July 24, 1973
3. Proposed American Nuclear Society Standard ANS-5.1, Decay Energy Release Rates Following Shutdown of Uranium-Fueled Thermal Reactors, (October 1971)
4. Roy A. Lindley, "Simulation of Natural Circulation in the Loss of Fluid Test Primary Coolant Loop", Master of Science Thesis (M.E.), University of Idaho (April, 1971) pp 7-10
5. LOFT FSAR, Rev. 1, Table 4-X
6. LTR 114-25 (TR-228), "LOFT Natural Circulation Study", R. C. Gottula, Nov. 9, 1971
7. LOFT FSAR, Rev. 1, Table 4-II

TABLE I

T_{IN}	T_2	$\bar{T}$	$\bar{\mu} \cdot 10^5$	$\mu_2 \cdot 10^5$	$\bar{C}_p$	P	XMAX	TMAX
°F	°F	°F	lbm/ft-sec	lbm/ft-sec	Btu/lbm-°F	kW	inches	°F
500	600	550	1.95	2.01	.2489	1.4	26.9	605
	700	600	2.01	2.15	.2503	3.8	26.0	711
	800	650	2.09	2.26	.2520	6.6	25.6	817
	900	700	2.15	2.40	.2534	9.8	25.2	923
	950	725	2.16	2.45	.2542	11.45	25.0	976
	1000	750	2.20	2.50	.2550	13.2	24.9	1029
	1100	800	2.26	2.56	.2566	16.7	24.8	1136
	1200	850	2.33	2.68	.2581	20.4	24.7	1242
	1300	900	2.40	2.84	.2598	24.1	24.6	1349
	1400	950	2.45	2.91	.2613	27.9	24.5	1455
	1500	1000	2.50	3.1	.2630	31.8	24.3	1562
	1600	1050	2.54	3.2	.2645	35.8	24.3	1669
	1800	1150	2.62	3.44	.2675	43.7	24.1	1883

TABLE II

TIN	T2	$\bar{T}$	$\bar{\mu} \cdot 10^5$	$\mu_2 \cdot 10^5$	$\bar{C}_p$	P	XMAX	TMAX
°F	°F	°F	lbm/ft-sec	lbm/ft-sec	Btu/lbm-°F	kW	inches	°F
400	600	500	1.88	2.01	.2474	4.3		611
	800	600	2.01	2.26	.2503	11.2		825
	900	650	2.09	2.40	.2520	15.0		933
	1000	700	2.15	2.50	.2534	18.9		1040
	1100	750	2.20	2.56	.2550	23.0		1147
	1200	800	2.26	2.68	.2566	27.2		1254
	1300	850	2.33	2.84	.2581	31.4		1362
	1400	900	2.40	2.91	.2598	35.7		1468
	1500	950	2.45	3.1	.2613	40.0		1577
	1600	1000	2.50	3.2	.2630	44.4	23.4	1684
	1800	1100	2.56	3.44	.266	53.2		1900

TABLE III

TIN	T2	T	$\bar{\mu} \cdot 10^5$	$\mu_2 \cdot 10^5$	$\bar{C}_p$	P	TMAX
°F	°F	°F	lbm/ft-sec	lbm/ft-sec	Btu/lbm-°F	kW	°F
300	600	450	1.81	2.01	.2462	8.8	621
	800	550	1.95	2.26	.2489	17.3	839
	900	600	2.01	2.40	.2503	21.8	948
	1100	700	2.15	2.56	.2534	31.05	1163
	1200	750	2.20	2.68	.2550	35.8	1272
	1300	800	2.26	2.84	.2566	40.6	1381
	1400	850	2.33	2.91	.2581	45.4	1488
	1550	925	2.42	3.15	.2606	52.7	1651
	1750	1025	2.52	3.35	.2638	62.5	1866

FIGURE 1
MAXIMUM FUEL CLAD
TEMPERATURE VS. TOTAL
HEAT GENERATION IN
THE LOFT REACTOR
FOR NATURAL CONVECTION
COOLING BY DRY AIR

FIGURE 3

LOFT PCS LOOP MODEL FOR
AIR NATURAL CIRCULATION ANALYSIS

FIGURE 4

AIR NATURAL CIRCULATION ANALYSIS
SOLUTION DIAGRAM